ABSTRACT

A Microgrid (MG) test model derived from the 14-bus IEEE distribution system is presented. This model serves as a valuable research tool for examining the evolution of electrical grids toward Smart Grids (SG). The benchmark system provides a foundational framework for power flow analysis and evaluates quality metrics associated with SG, integrating distributed energy resources. The MG includes both DC and AC buses, incorporating various load types and distributed generation across two voltage levels. The comprehensive model has been developed and simulated using the MATLAB/Simulink platform. This electrical system acts as a reference point for studies involving reactive power compensation, stability and inertia analysis, reliability, demand response mechanisms, hierarchical control, fault-tolerant operations, optimization techniques, and energy storage solutions.

Keywords: *Electrical engineering, System diagnostics, Power system operation, Power converter, Smart grid technology, Distributed resources, Microgrid benchmark, Hybrid energy systems, Power flow*

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ABBREVIATIONS

MG	**Microgrid**
SG	**Smart Grids**
LV	**Low Voltages**
MV	**Medium Voltages**
VSC	**Voltage Source Converters**
RES	**Renewable Energy Sources**
LTI	**Linear and Time Invariant System**
Ni–MH	**Nickel-Metal-Hydride**
CMLI	**Cascade h bridge Multi Level Inverter**
MPPT	**Maximum Power Point Tracking Control**
PHEV	**Plug-in Hybrid Electric Vehicle**
BESS	**Battery Energy Storage System**

CHAPTER 1

INTRODUCTION

1.1 Introduction

Renewable energy systems (RES) have emerged as a cleaner and more sustainable technology to meet the increasing electricity demands of both interconnected and isolated communities. Over recent years, Microgrids (MGs) have gained significant attention in the scientific community as a promising solution for integrating renewable energy systems into traditional power grids. With advancements in digital technologies, such as micro-processed systems and power electronics, many applications have been developed for smart grids (SGs), especially focusing on controllers and electronic energy converters.

Microgrids provide an effective way to integrate distributed generation into the main grid in a reliable and clean manner. They offer high reliability in operation, even in the face of natural events and disturbances, thereby minimizing energy losses during transmission and reducing construction and investment time. Numerous real-world implementations of MGs have been seen in various countries, including the US, Japan (NEDO), and across Europe.

A Microgrid can be defined as a low-voltage power system that connects small, modular generation systems (like renewable energy sources) and energy storage units to meet local electricity demand. MGs can either work as a controllable load or generator when connected to the utility grid. While MG configurations can be based on DC, AC, or a hybrid of both technologies, research is particularly focused on AC-based MGs due to their compatibility with the main grid.

The dynamic behavior of distributed generators, the nonlinearity and imbalance of electrical loads, and the management of energy storage systems are some of the critical challenges faced by MGs. Moreover, Hybrid Microgrids (HMGs) must also deal with unexpected or planned disconnections from the main grid. The effectiveness of HMGs can be tested in various scenarios, such as minimum and maximum demand situations, to examine how they manage abnormal operations.

Power electronics play an important role in MGs, as most renewable generation technologies require converters to control the injected power. By implementing closed-loop control strategies, the power quality challenges can be mitigated. The performance of MG systems can be improved through parallel inverters, optimizing their operation.

In this study, a detailed model of a Hybrid Microgrid (HMG) has been simulated, based on the IEEE-14 distribution-bus model. This model primarily focuses on solar energy as the renewable source, excluding wind energy, as one energy source is typically more available than the other. The goal of this study is to create a comprehensive model for further studies, including reliability, optimization, fault diagnosis, system identification, and fault-tolerant control.

The study also incorporates various components, such as photovoltaic systems, battery energy storage systems, and power converters. Both open-loop and closed-loop control strategies are employed to manage power flow efficiently. Additionally, typical balanced and unbalanced loads, linear and nonlinear loads, and distribution transformers are included in the model.

The simulations are carried out using MATLAB/Simulink, where two scenarios—maximum demand and minimum demand—are analyzed. The study presents results showing how bidirectional power flows and the integration of solar photovoltaic generation impact the system.

1.2 Literature Survey

Name Of Paper	Authors	Year Of Publication	Key Takeaways
A Hybrid AC/DC Micro-Grid Architecture, Operation and Control	Peng Wang Xiao Lin	July 2011	Explores the architecture, operational modes, and control strategies for hybrid micro-grids. These systems aim to enhance energy efficiency and reliability in power distribution networks by integrating both AC and DC power sources and loads.
Hybrid AC/DC Microgrids—Part I: Review and Classification of Topologies	Jon Barrena	December 2015	Explores the integration of renewable energy sources into power systems through hybrid microgrids, which can enhance reliability, efficiency, and sustainability.
Hybrid AC/DC Microgrid Test System Simulation: Grid-Connected Mode	Gabriel C. Hug Alexander	November 2019	Explores the integration of renewable energy sources and the improvement of power system operations through such hybrid microgrids.
A Hybrid AC/DC Microgrid with Multi-Bus Optimal Operation	Bhavana Pabbu Dr. Somashekhar	December 2022	Focuses on economic operation costs and control strategies for these microgrids, aiming to enhance efficiency and reliability in power distribution networks.

1.3 Objectives

1. Simulate a detailed Hybrid AC/DC Microgrid using MATLAB/Simulink.
2. Integrate Solar PV, Diesel Generator, and Battery Storage Systems.
3. Analyze system under Maximum and Minimum Demand.
4. Evaluate Voltage Profile, Power Flow, Power Factor, and THD.

CHAPTER 2

PROPOSED SYSTEM

2.1 Introduction

Hybrid Microgrids (HMGs) are gaining increasing attention as a viable solution for integrating renewable energy systems and improving the efficiency of power distribution. These systems can be implemented in both medium-voltage (MV) distribution grids or low-voltage (LV) residential areas. When designing an AC/DC HMG, several key requirements need to be considered to ensure the system's effective operation. These include factors like reliability, controllability, observability, economy, and flexibility.

The design of an HMG must adhere to a set of guiding principles to optimize performance and resource use. Among these principles are the **principle of partition**, which divides the system into manageable segments, and the **principle of hierarchy**, which organizes the system for better control and management. Maximizing the use of available resources and ensuring **energy complementarity** are critical for efficient energy production and consumption. Furthermore, ensuring **power quality assurance** and proper **storage allocation** is crucial to maintain a stable and reliable energy supply. **Reactive power compensation** also plays a vital role in maintaining system stability.

Finally, the design of HMGs often follows specific configurations, such as **radial** or **ring** topologies, which define the structure of the distribution network. These configurations help determine how power is distributed and managed within the grid, ensuring optimal performance and resilience under various operational conditions.

2.2 Block Diagram

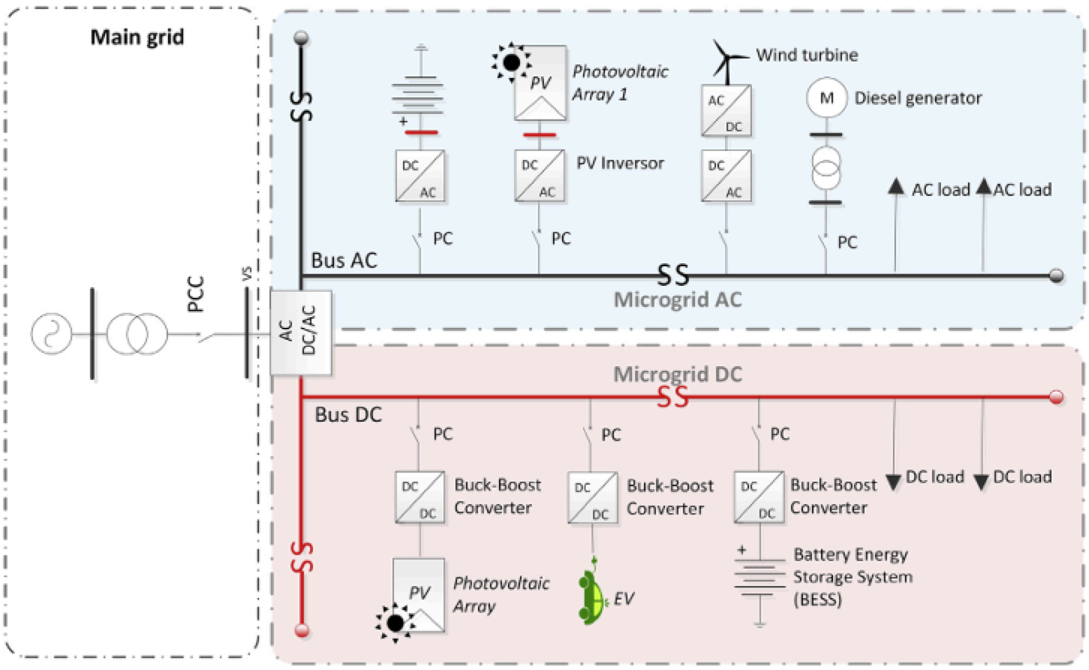


Fig 2.2.1 : Block Diagram of Proposed System

2.3 Software Used

MATLAB SIMULINK

CHAPTER 3

METHODOLOGY ADOPTED

3.1 Introduction

The methodology involves developing a Microgrid (MG) test model based on the 14-bus IEEE distribution system. The model integrates DC and AC buses with various loads and distributed generation across two voltage levels. MATLAB/Simulink is used for simulation, providing a platform to study power flow, grid quality, and advanced control strategies like stability, demand response, and energy storage optimization.

3.2 Implemented Model

●Microgrid is coupled to a 69 kV electrical subtransmission system.

●Two voltage distribution levels

a) 13.8 kV

b) 220 V

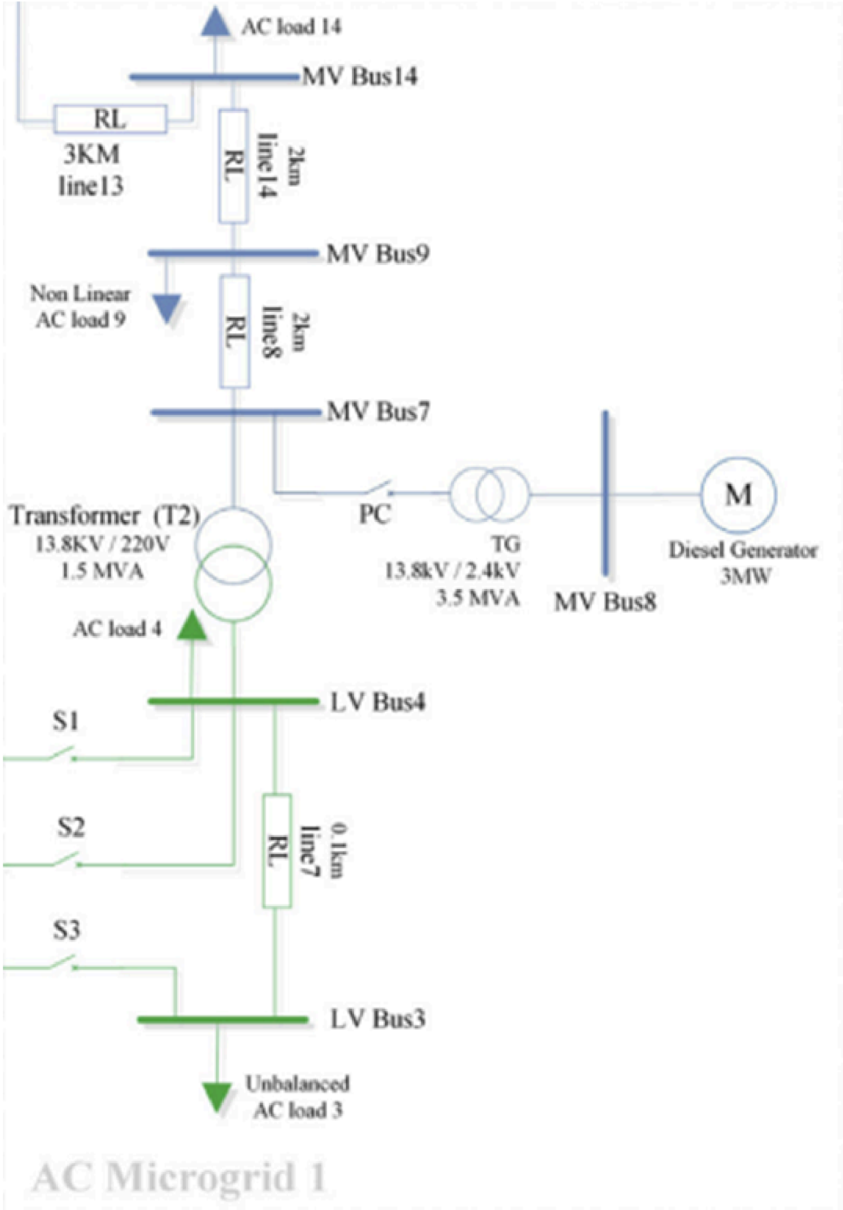
● 3 Sub Microgrids

a) AC Microgrid 1

b) AC Microgrid 2

c) DC Microgrid

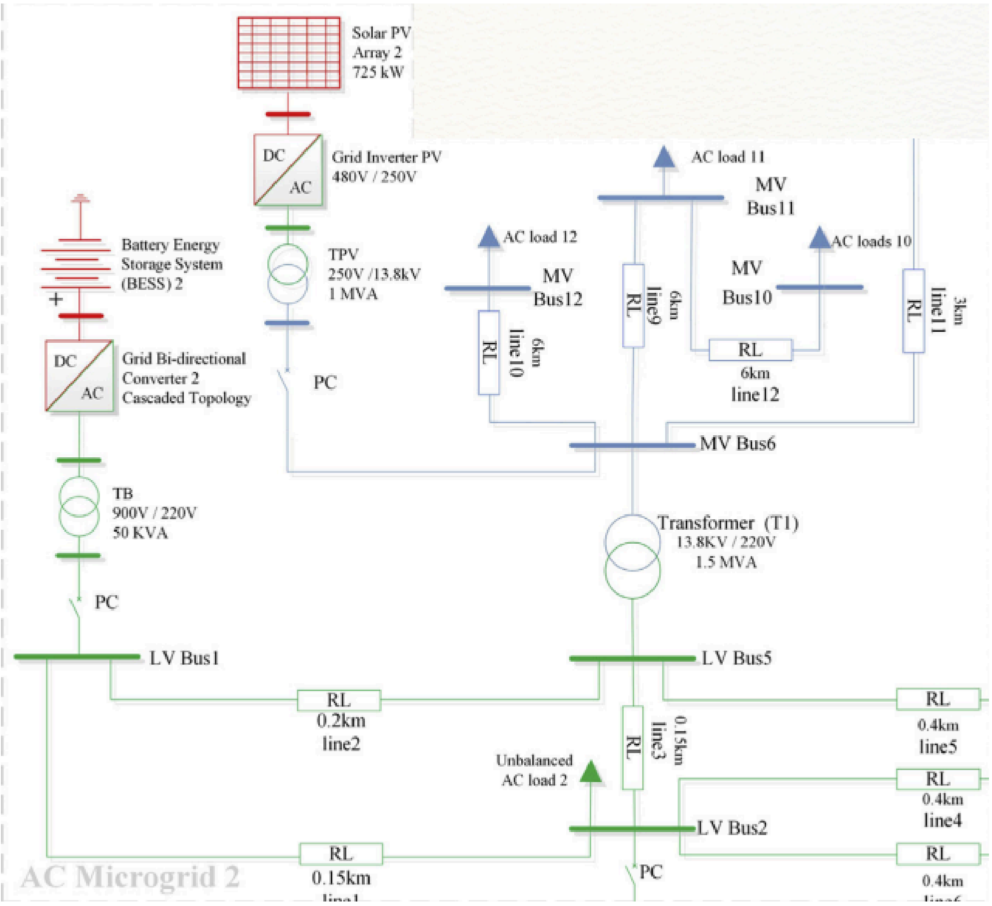
3.2.1 Section 1 - AC Microgrid 1



DIESEL GENERATOR	3MW Capacity
Transformer (TG)	3.5 MVA , 2.4kV/13.8kV
Transformer T2	1.5 MVA , 13.8kV/220V

Load	Bus	Max Load (kVA)	Min Load (kVA)	PF
Load 3 (Unbalanced-12.6%)	LV3	30	9	0.85
Load 4 (Linear)	LV4	50	15	0.9
Load 9 (Non-Linear)	MV9	320	96	1
Load 14 (Linear)	MV14	1600	480	0.8

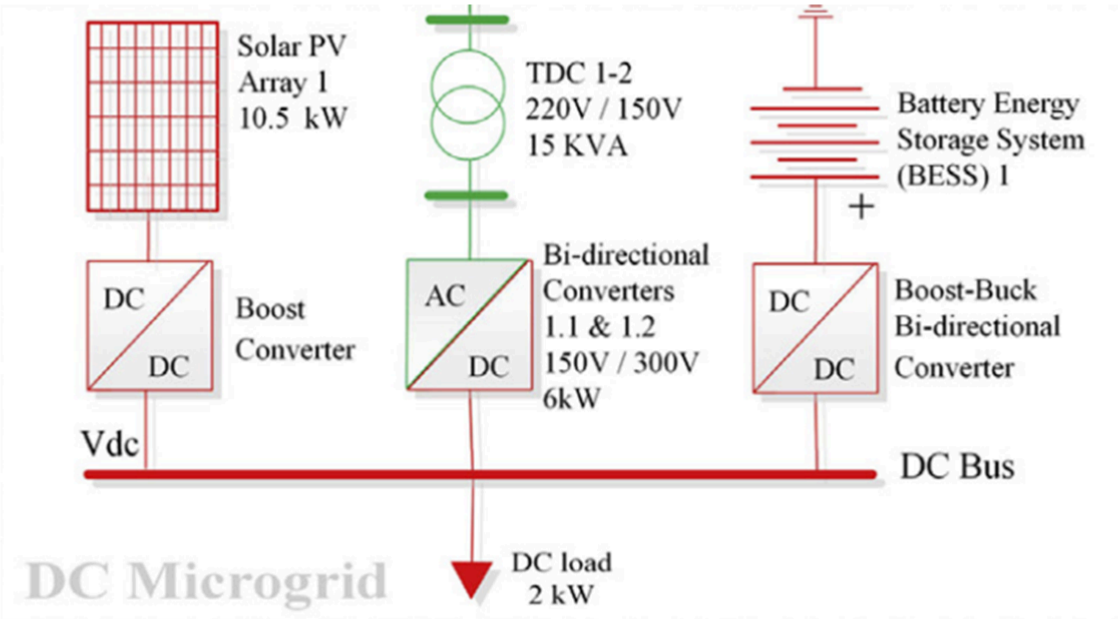
3.2.2 Section 2 - AC Microgrid



Solar PV	725kW
Battery Energy Storage System (BESS - 2)	3nos. Nickel-Metal-Hydride (650 VDC, 1.5 Ah)
Transformer (TPV)	1MVA , 250V/13.8kV
Transformer (TB)	50kVA , 900V/220V
Transformer (T1)	1.5MVA , 13.8kV/220V
Grid Inverter PV	DC-AC , 480V/250V
Grid Bi-directional Converter	DC-AC , 650V/900V

Load	Bus	Max Load (kVA)	MIn Load (kVA)	PF
Load 2 (Unbalanced-13 %)	LV2	40	40	0.9
Load 10 (Linear)	MV10	800	240	0.8
Load 11 (Linear)	MV11	400	120	0.8
Load 12 (Linear)	MV12	800	240	0.8

3.2.3 Section 3 - DC Microgrid



Solar PV	10.5kW
Bi-directional Converters	AC-DC , 6kW , 150V/300V
Transformer (TDC 1-2)	15kVA , 220V/150V
Boost Converter	PWM - 5000 Hz

Load	**Bus**	**Max Load (kW)**	**Min Load (kW)**	**PF**
DC Load	DC Bus	2	0.6	1

Table 1

PV arrays for the MG system

ID	**Current at maximum power point Impp (A)**	**Maximum Power (W)**	**Open circuit voltage Voc (V)**	**Voltage at maximum power point Vmp (V)**	**Short circuit current Isc (A)**
Array 1	8.63	250	37.4	30.7	8.63
Array 2	5.69	414.8	85.3	72.9	6.09

The Simscape library integrates Eqs. (1), (2), (3), and (4) which govern the discharge-charge process of the nickel-metal-hydride batteries

$$E_{disch}^{\mathrm{Ni-MH}} = Eo - k\frac{Q}{Q-it}i^{*} - k\frac{Q}{Q-it}it + Exp(t) \tag{1}$$

$$E_{ch}^{\mathrm{Ni-MH}} = Eo - k\frac{Q}{|it|-0.1Q}i^{*} - k\frac{Q}{Q-it}it + Exp(t) \tag{2}$$

The discharge condition implies i * > 0 while the charge condition implies i * < 0. On the other hand, the equations that govern the discharge-charge process of the lithium-ion batteries are:

$$E_{disch}^{\text{Li-Ion}} = Eo - k\frac{Q}{Q - it}i^{*} - k\frac{Q}{Q - it}it + AExp(-Bit) \quad (3)$$

$$E_{ch}^{\text{Li-Ion}} = Eo - k\frac{Q}{|it| - 0.1Q}i^{*} - k\frac{Q}{Q - it}it + AExp(-Bit) \quad (4)$$

The discharge-charge conditions are the same as those of the Ni–MH battery type.

Table 2

Transformer ratings for the MG system.

Transformer	Nominal Power (kVA)	Voltage Ratio (HV/LV)	Rcc (pu)	Xcc (pu)
T1	1500	Y 13800/220 Y	0.03	0.03
T2	1500	Y 13800/220 Y	0.03	0.03
T3	4000	Yg 69000/13800 D1	0.015	0.015
TB	55	D1 900/220 Y	0.003	0.06
TG	3500	Yg 13800/2400 D1	0.015	0.015
TPV	1000	Yg 13800/250 D1	0.0012	0.03
TDC1-2	15	Y 220/150 Y	0.03	0.06

Table 3

Line data for the MG system

Line	**Sending end**	**Receiving End**	**R (ohm)**	**X (ohm)**	**Distance (km)**
1	LV1	LV2	0.0297	0.016335	0.15
2	LV1	LV5	0.0396	0.02178	0.2
3	LV2	LV5	0.0297	0.016335	0.15
4	LV2	LV4	0.0792	0.04356	0.4
5	LV4	LV5	0.0792	0.04356	0.4
6	LV2	LV3	0.0792	0.04356	0.4
7	LV3	LV4	0.0198	0.01089	0.1
8	MV7	MV9	0.788	0.2336	2.0
9	MV6	MV11	2.364	0.7008	6.0
10	MV6	MV12	2.364	0.7008	6.0
11	MV6	MV13	1.182	0.3504	3.0
12	MV10	MV11	2.364	0.7008	6.0
13	MV13	MV14	1.182	0.3504	3.0
14	MV9	MV14	0.788	0.2336	2.0

Unbalanced Load Percentage Equation

$$UL\% = \frac{max\ \{|I_a - I_{average}|\ ;\ |I_b - I_{average}|\ ;\ |I_c - I_{average}|\}}{I_{average}} * 100 \tag{5}$$

$$\boldsymbol{I_{average}} = \frac{I_a + I_b + I_c}{3} \tag{6}$$

Where Ia , Ib , Ic are the line rms currents in phase a , b and c.

Critical Inductance and Capacitance Equation

$$L_c = \frac{D\,(1 - D)}{2f}\,R \tag{7}$$

$$C_c = \frac{D}{2fR} \tag{8}$$

Lc, is the inductance critical value

Cc, is the capacitance critical value

D, is the duty cycle

f , is the switching frequency

R, is the load resistance

Ripple Calculation Equations (Buck-Boost Converter)

$$\Delta I_{HV\ side} = \frac{V_i}{fL}\,D \tag{9}$$

$$\Delta V_{HV\ side} = \frac{I_o}{fC}\,D \tag{10}$$

$$\Delta I_{LV\ side} = \frac{V_o\,(V_i -\ V_o)}{fL\,V_i}\,D \tag{11}$$

$$\Delta V_{LV\ side} = \frac{V_i}{8\,L\,C\,f^2}\,D\,(1 - D) \tag{12}$$

ΔI_{HV}, Inductor Current for Boost Side

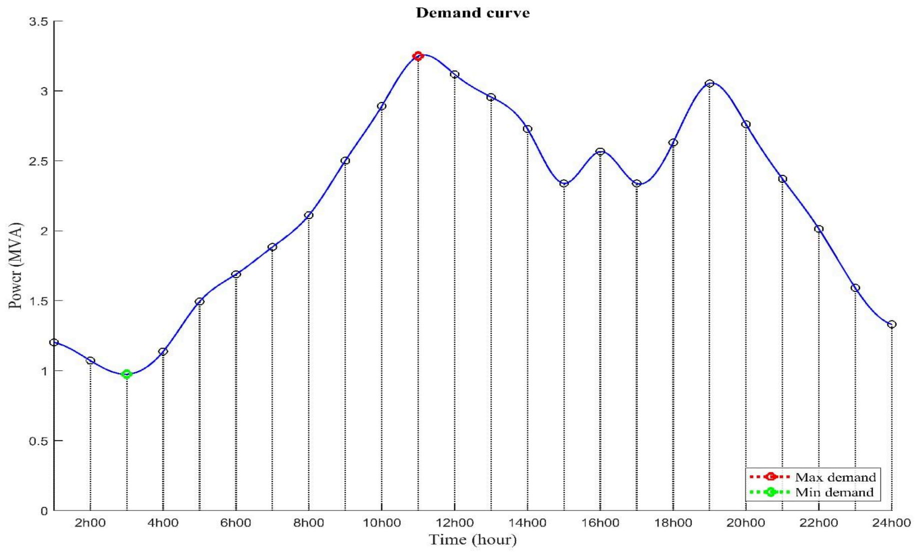
ΔV_{HV}, Capacitor Voltage Ripple for Boost Side

ΔI_{LV}, Inductor Current for Buck Side

ΔV_{LV}, Capacitor Voltage Ripple for Buck Side

3.3 LOAD FLOW SCENARIO

- To compute metrics that allow defining a base case for future optimization and compensation studies , two analysis scenarios are defined
- Scenario 1 - Maximum Demand (Around 3MVA)
- Scenario 2 - Minimum Demand (30% of Maximum Demand)



Generation	Maximum Demand	Minimum Demand
Main Grid	Connected	Connected
Solar PV Array 1 & 2	Generating at 1000 W/m^2	OFF
BESS 1	Charge at 5A	Charge at 3A
BESS 2	Generate	Charge
BiDirectional Converter 1&2	Inverter	Rectifier
Diesel Generator	Generating	Generating

future analysis to be established in terms of reactive power compensation. The capacity and location of the compensating devices must be determined considering the minimum demand scenario. In fact, the voltage profile of the system could reach overvoltage levels with the reactive injection of the compensating devices.

In Fig. it can also be seen that the maximum demand period is at 11h00, which coincides with the peak of solar radiation and, therefore, with the maximum generation capacity of the solar panels. This demand peak during this time is due to the integration of industrial load curves with residential load curves."

3.4 Voltage Profile Analysis

It is a evaluation of voltage magnitudes at various buses in a power system under specific load and generation conditions . It is crucial for **System reliability , Energy efficiency , Power quality**

Good Voltage Profile

1. Line to Line Voltage is close to 1.0 pu
2. Has minimal dips or surges
3. Uniform across phases

Average Deviation of Voltage

$$ADVS = \frac{\sum_{i=1}^{n} |Vd_i - V_i|}{n}$$

Where,
n is the number of buses in the MG
Vi is the real voltage at bus i in pu
Vdi is the desired voltage at bus i in pu (1pu)
Maximum Value of Voltage Deviation

- Voltage varies across buses and phases.
- Bus2AC has potential undervoltage risk .
- Most voltages are within acceptable range of 0.95-1.05pu.

Matlab Code for calculation of ADVS & ADVS max

```
% ADVS & ADVS max
     u = ones (length (VoltageLL_pu_AC_bus), Phase);
  ADVSabc = abs( u -  VoltageLL_pu_AC_bus);
     ADVS = sum (ADVSabc)/length (ADVSabc);
  ADVmax = max (ADVSabc) %
```

ADVS : Phase A - 0.0568
Phase B - 0.0412
Phase C - 0.0499

3.5 Active and Reactive Power Balancing

Active Power Balancing

1. Ensures that power from PV arrays, Diesel generators and BESS matches the load + losses .
2. Should behave differently in Maximum (high PV, Diesel support) and Minimum (no PV, higher diesel/grid) demand conditions .

Reactive Power Balancing

1. Mainly provided by Diesel Generator and Main Grid .
2. Affected by Load Type (Inductive load consumes Q) , Power Electronics (can generate or absorb Q) .
3. Essential for Voltage Control and Stability .

Power Flow Equations

$$P_i = \sum V_i V_j (G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij})$$

$$Q_i = \sum V_i V_j (G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij})$$

where, Pi and Qi are the net active and reactive powers at bus i
.

3.5 Power Factor and Losses

In Hybrid AC/DC Microgrids power factor and losses directly affect system efficiency, energy quality and component lifespan .

Power Factor is the ratio of real power to apparent power

$$\text{Power Factor} = \frac{\text{Active Power (kW)}}{\text{Apparent Power (kVA)}}$$

Power Losses occur mainly due to the resistance of conductors and are proportional to the square of the current.

$$\text{Loss} = I^2 \cdot R$$

To reduce power losses

1. Improve Power factor.
2. Balance loads.
3. Use lower resistance cables.
4. Optimize control of converters and storag

3.7 Total Harmonic Distortion (THD) Analysis

THD analysis measures how much the voltage or current waveform in a power system deviates from a pure sinusoidal shape due to the presence of harmonics.

Harmonic	Frequency (Hz @ 50Hz base)	Source Example
2nd	100	Power electronics
3rd	150	Saturated transformers
5th	250	Inverters, rectifiers

$$\text{THD } (\%) = \frac{\sqrt{V_2^2 + V_3^2 + \cdots + V_n^2}}{V_1} \times 100$$

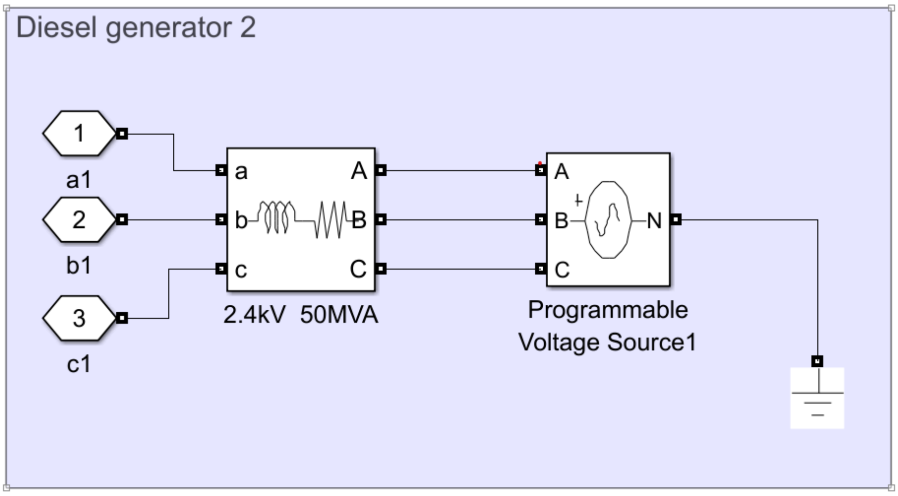
where, V1: RMS value of the fundamental
V2,V3….,Vn: RMS values of harmonic component

CHAPTER 4

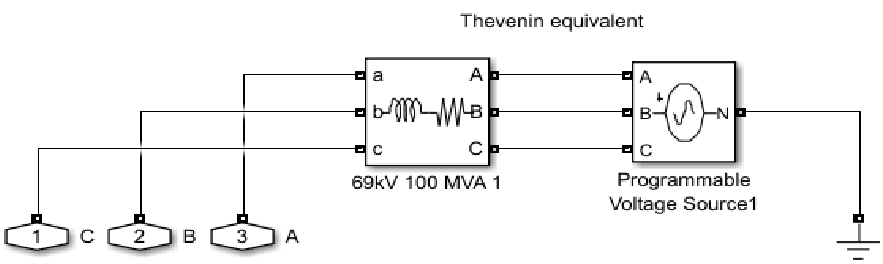
RESULTS AND FUTURE SCOPES

4.1 Matlab Simulation

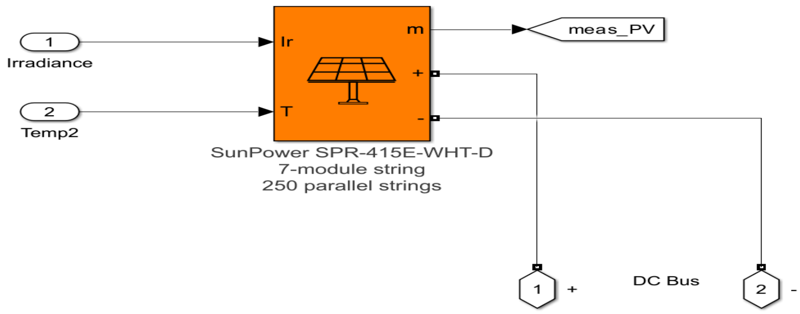
Diesel Generator



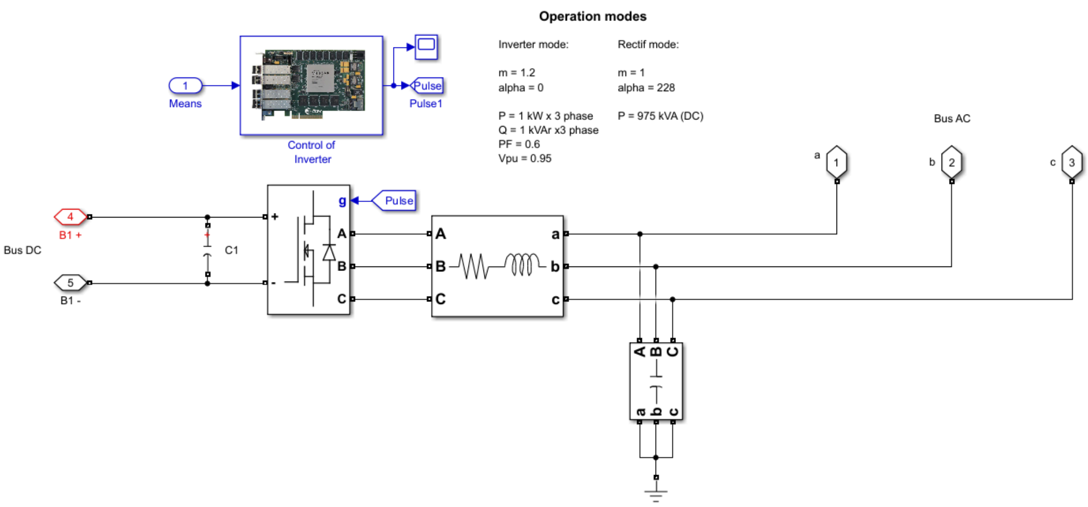
Main Grid



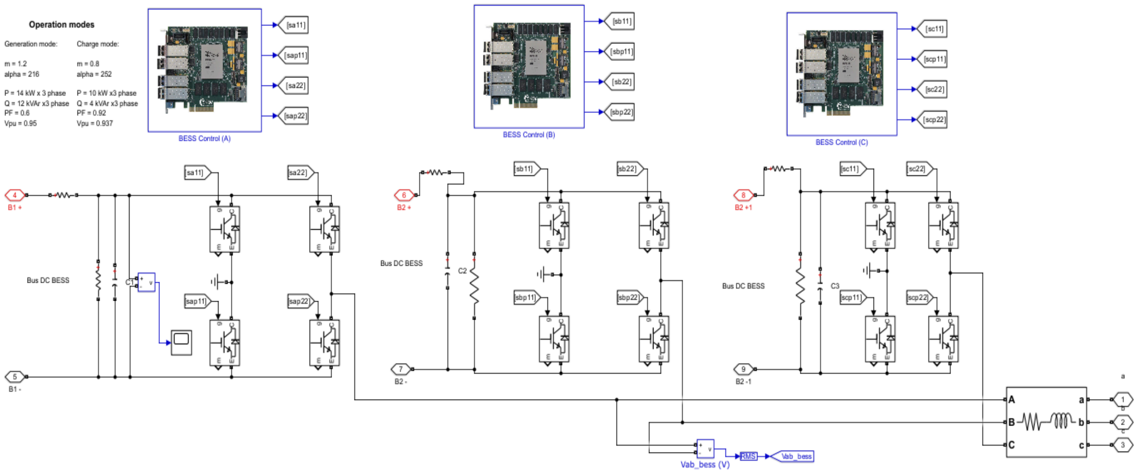
PV Array



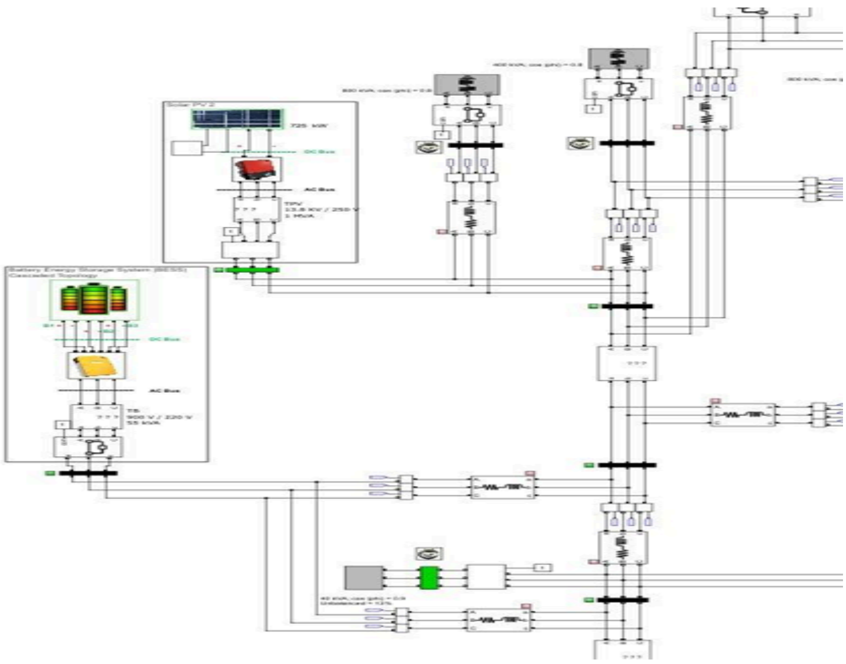
Bidirectional Converter DC-AC



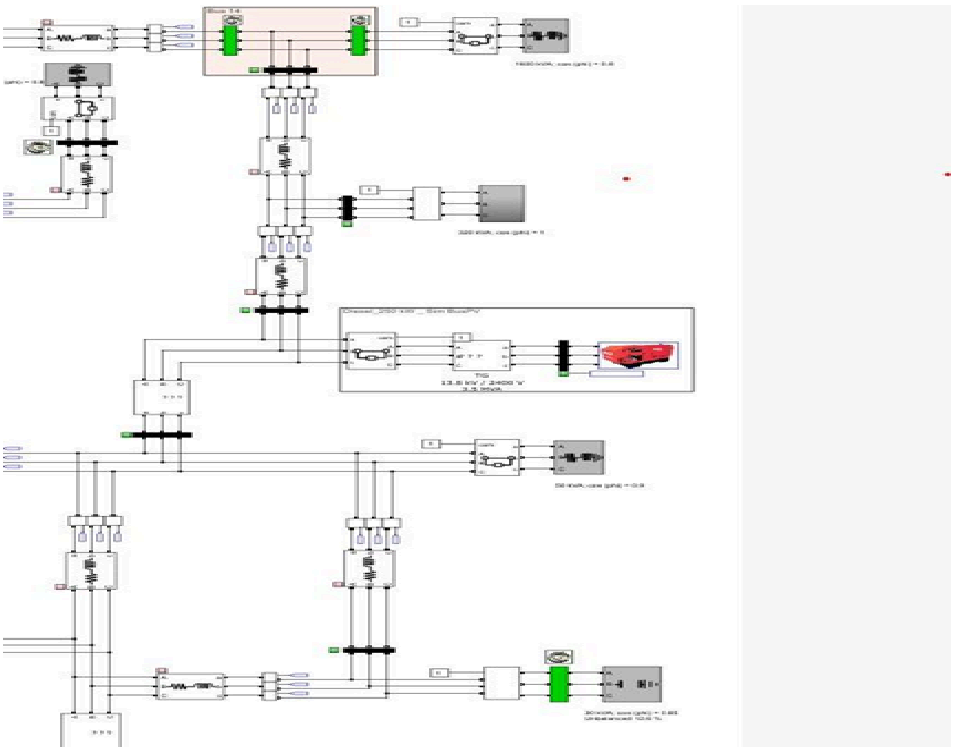
Grid Bidirectional Converter



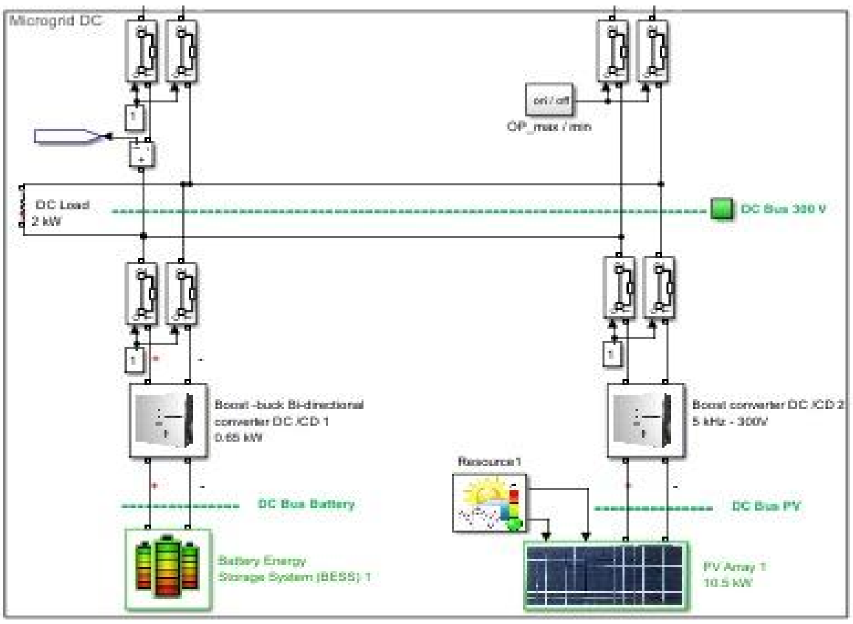
AC Sub-Microgrid 1



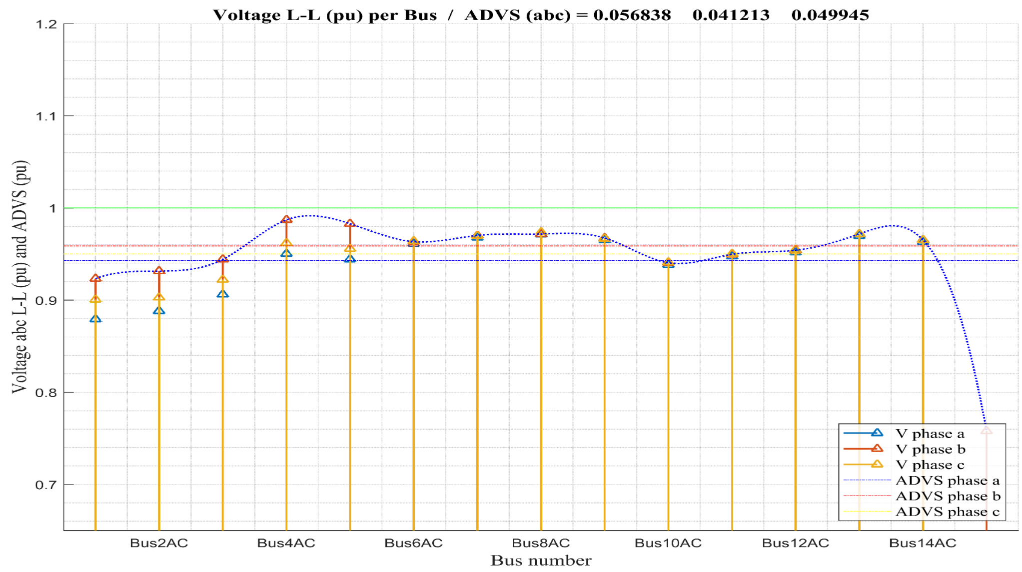
AC Sub-Microgrid 2



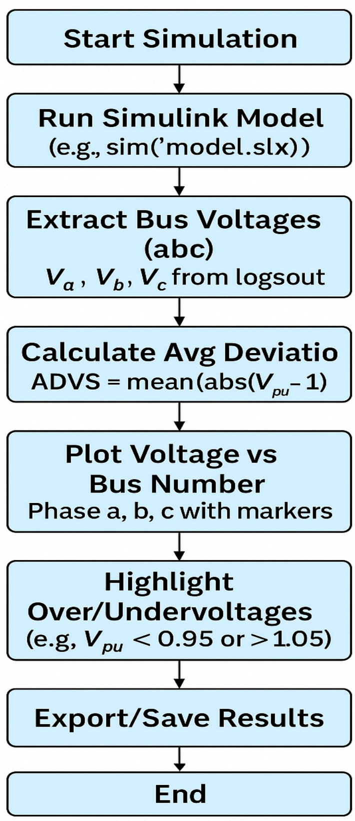
DC SUB-MICROGRID



4.3 Voltage Profile Analysis

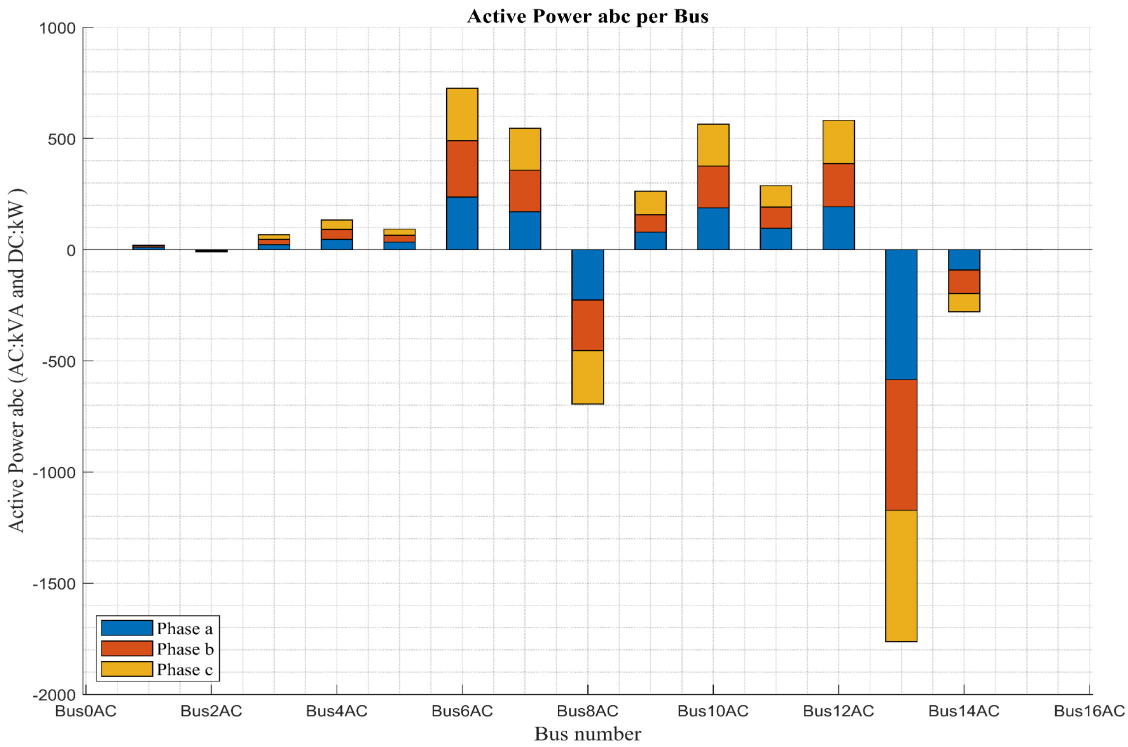


- Voltage varies across buses and phases.
- Bus2AC has potential undervoltage risk .
- Most voltages are within acceptable range of 0.95-1.05pu.



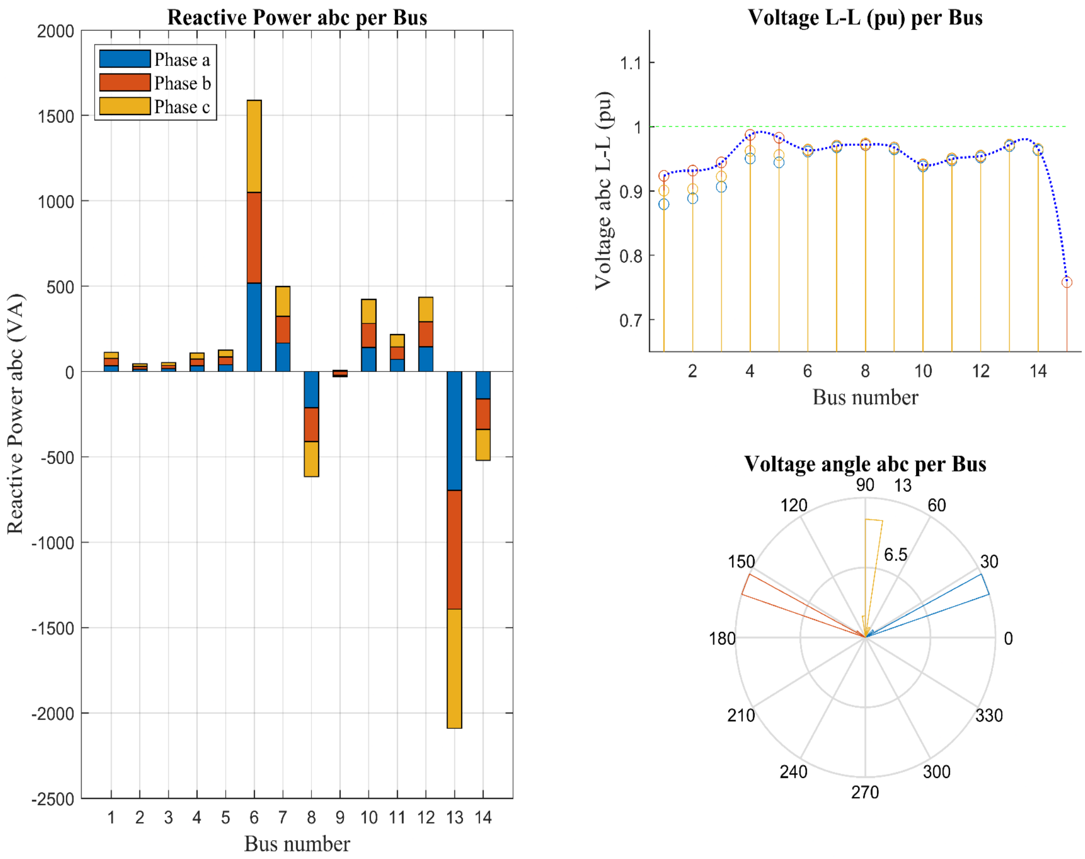
3.5 Active and Reactive Power Balancing

Active Power abc per bus



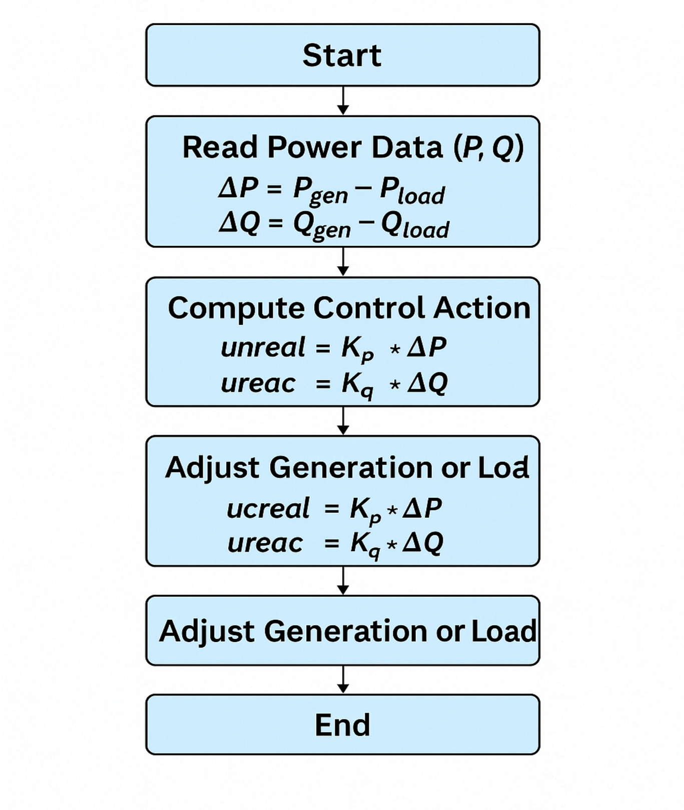
- **Positive bars** indicate **load consumption.**
- **Negative bars** show **power generation.**
- Major generation at Bus8AC(Diesel generator), Bus12AC & Bus14AC (Grid and converter source).
- High consumption at Bus4AC,Bus6AC,Bus10AC (Load Centers).
- **Power is well distributed** across all 3 phases.
- **Effective operation** under high demand with distributed generation support.

Reactive Power and Voltage Angle analysis



- Positive Q - Buses injecting reactive power.
- Negative Q - Buses absorbing reactive power.
- Voltage drops significantly at Bus14AC, indicating stress due to reactive power absorption.
- Angular spread between phases is approximately 120° hence it is Balanced 3-phase system.
- Minor angular displacement due to phase loading imbalance.

Flowchart for Active and Reactive Power Analysis

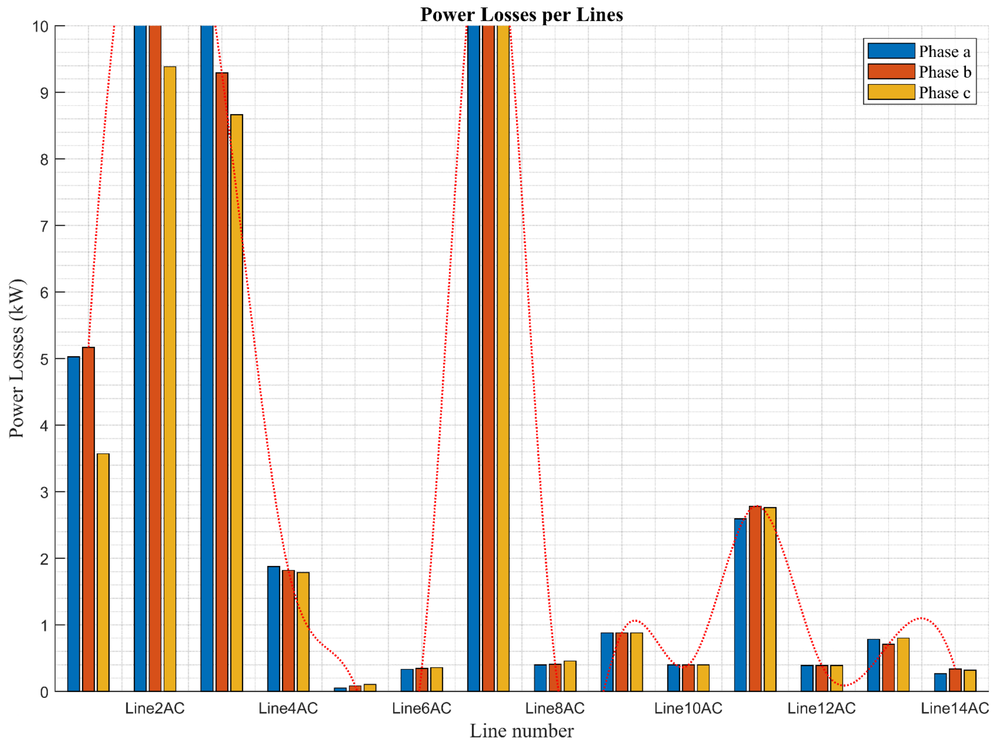


4.5 Power Factor and Losses

Power Factor

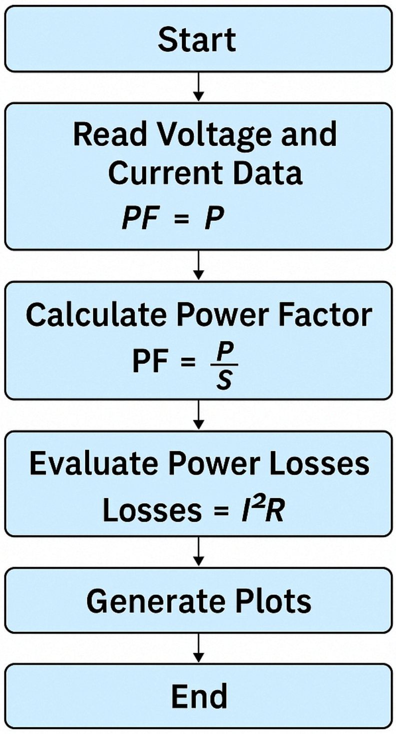
- Green Line - Unity power factor (ideal).
- Best PF at Bus10AC & Bus12AC, efficient power usage and balanced loading.
- Lowest PF at Bus2AC & Bus6AC ,significant reactive power flow
- Bus14AC shows moderately low PF, suggesting it is a load heavy bus.
- Low PF leads to higher losses
- System would benefit from reactive compensation.

Power Losses



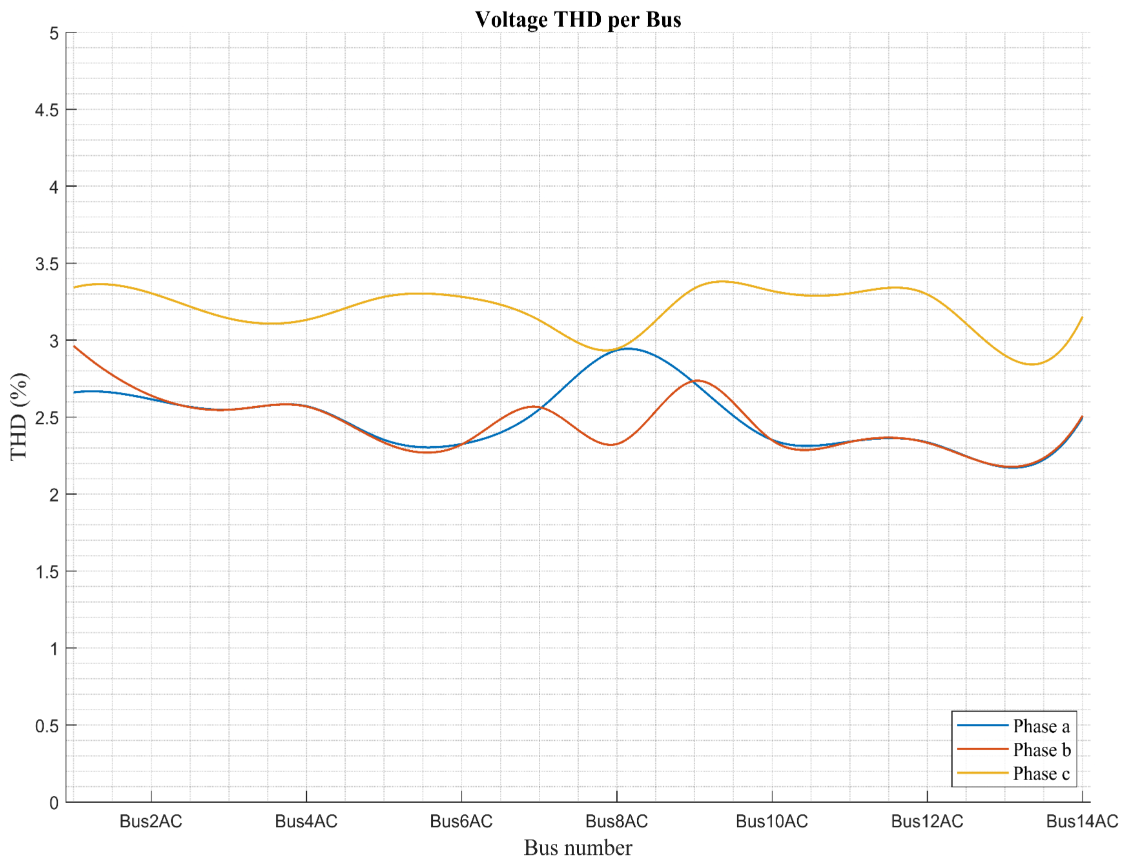
- Highest Losses - Line4AC & Line8AC , Due to long distance, high current & low PF.
- Moderate Losses - Line2AC & Line10AC.
- Minimal Losses - Line6AC, Line12AC & Line14AC.
- Balanced losses across phases (a,b,c) in most lines , except slight imbalance in heavily loaded lines.

Flowchart for Power Factor and Power Loss Analysis



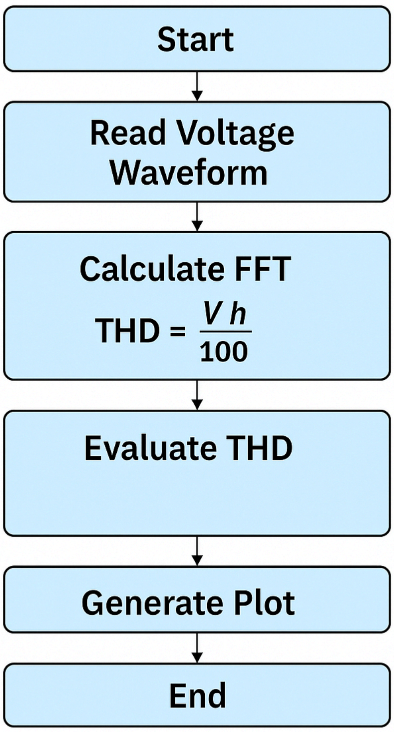
4.6 Total Harmonic Distortion (THD) Analysis

Voltage THD per Bus



- THD remains below 3.5% across all buses and phases within IEEE 519 Standards(<5%).
- Phase C consistently has the highest THD (upto 3.4%) at most buses.
- Lowest THD observed at Bus6AC & Bus10AC (2.3%).
- Slight variation between phases indicates harmonic imbalance.
- Acceptable THD indicates good power quality.

Flowchart for THD Analysis



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